Numerical Tsunami Model in Osaka Bay*

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Abstract

A numerical experiment was undertaken to find what combination of tsunami source parameters was reasonable for an understanding of the dynamics of a tsunami inundating into a bay. Finite difference method was applied to the basic equations of long waves. The modelled area included Osaka Bay, Kii Channel, Harimanada and a part of the northwestern Pacific Ocean. In addition, the arrival time of the leading wave is discussed in reference to the results of the numerical experiment. The numerical results compare reasonably well with those from an observed tsunami.

1. Introduction

A numerical experiment was undertaken to find what combination of tsunami source parameters was reasonable for a dynamical understanding of a tsunami in a bay. A simple finite difference method was applied to the basic equations of long waves. The computer programme utilized was originally developed as a package programme for the time stepping of long waves into the coastal region (Loomis, 1972)[1], and modified by Nakamura (1980)[2] for a numerical simulation of the 1977 Sumbawa Tsunami. For convenience in the present numerical experiment, the area of consideration was taken to include Osaka Bay, Kii Channel, Harimanada and a part of the Pacific Ocean.

There are many studies of tsunamis which have inundated into Osaka Bay (cf. for example, papers compiled in a bibliography published by the U.S. Coast and Geodetic Survey, 1964)[3]. Many Japanese scientists have worked on this problem both theoretically and experimentally. On the basis of old records, reconnaissance reports (for example, Hatori, 1980)[4] and tsunami catalogues (Iida et al., 1967[5]; Soloviev and Gao, 1974)[6], we can easily find the greatest tsunamis observed in Osaka: these are in 1707 Hoei, 1854 Ansei, 1944 originating in the south of Japan, in 1946 in Nankaido and in 1960 off the Chilean coast. As for the estimation of the historical tsunami source, an inverse wave front propagation method has been widely utilized for a long time (e.g., Hatori, 1974)[7]. In this study, the tsunami source was taken to be located at almost same plcace as the estimated front of the 1946 tsunami.

The coastal area around Osaka Bay has been highly utilized as an urban area and for industries. Therefore, it is also necessary to find whether countermeasures for any storm surge in Osaka Bay are enough even for any tsunami, even though countermeasures for storm surge have been almost completely established along the

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coast in Osaka Bay. The author believes that the numerical experiment developed in this study is helpful to evaluate tsunami countermeasure plans and designs in relation to the storm surge countermeasures.

In this study, the focus is mainly on the properties of the leading wave of the modelled tsunamis numerically, after introducing several parameters which characterize the tsunami source in the model. In addition, the arrival time of various tsunamis is discussed on the basis of the numerical experiment.

2. Design Conditions

In this study, a simple finite difference method is utilized which is already familiar and has been applied to the propagation of long waves in a coastal area by Loomis (1972)[1]. This scheme was modified for the numerical experiment of the 1977 Sumbawa Tsunami by Nakamura (1980)[2] and by Allison and Nakamura (1982)[8]. For convenience of numerical computation, the computing programme was altered to fit the input data for the surface condition in the source area. In this study, an equivalent source condition was considered to exist on the sea surface.

2.1 Bathymetry

The bathymetry and coastlines in the area of interest are shown schematically in **Fig. 1**, where the full lines show profiles of the coastline, and the dotted lines show depth contours in metric units. Generally speaking, the bathymetry and coastline are not simple in this area. A rectangular mesh with a spacing of 4540 m was taken as in **Fig. 1** to cover the area of the co-ordinates given by the I-axis and J-axis. The water depth at each mesh point was obtained by an interpolation, referring to a nautical chart (No. 100A) published by the Hydrographic Department, Maritime Safety Agency of Japan. The maximum water depth in the area for numerical computation was taken to be 2600 m.

2.2 Tsunami source parameters

The tsunami source was characterized by several parameters for the water surface condition in the numerical computation. These parameters could be later related to the seismic parameters indirectly or qualitatively, although combinations of these parameters for the surface condition of the tsunami source in the numerical model was selected simply for the convenience of numerical computation. The seismic parameters are found in the papers by Kanamori (1972[9], 1973[10]).

The tsunami source in this study was characterized by a vertical displacement W of the sea surface in the source area and by its duration time, T, as an equivalent disturbance of the sae surface in the source area, while displacement of the sea bed in the source area should be considered exactly for a tsunami. The behaviour of a tsunami along the coast depends on the location and properties of the source area. Therefore, the length, D, and width, B, of the source area and the location, F, of the initial wave front are introduced. The selected values of these parameters are shown

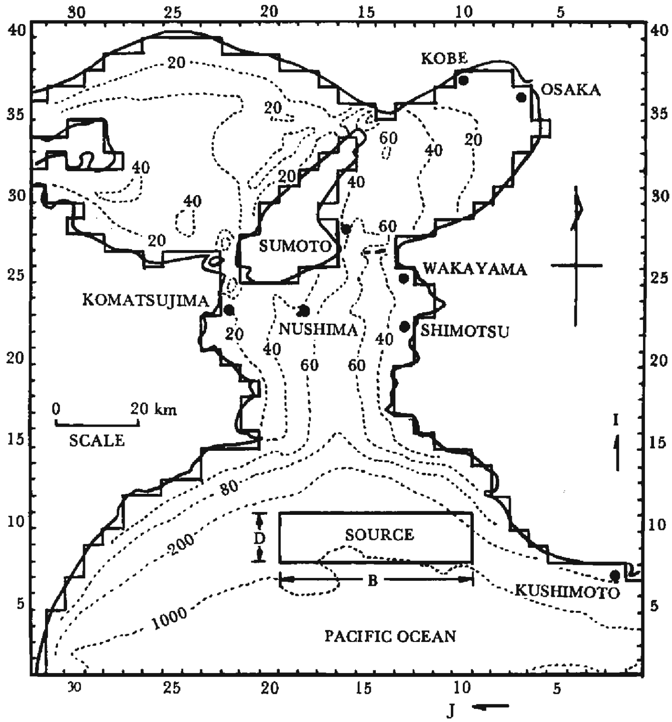

Fig. 1. The area for a numerical tsunami model (dotted lines are the bathymetric contours in the metric unit)

Table 1. Categories of tsunami source parameters.

Source Parameter \ Category	A	B	C	D	E
Vertical Displacement of Water Surface–W (m)	0.1	0.5	1.0	2.0	3.0
Duration Time of Disturbance–T (sec)	200.0	400.0	800.0	1200.0	1600.0
Size of Source					
Length–D*	$2\Delta x$	$3\Delta x$	$4\Delta x$	$5\Delta x$	$6\Delta x$
Position of Front F(I)	I=4	I=6	I=8	I=10	I=12
Width–B*	$10\Delta y$	$8\Delta y$	$6\Delta y$	$4\Delta y$	$2\Delta y$

* note: $\Delta x=\Delta y=4540$ m. Tsunami source is characterized by a combination of the parameters such as W, T, D, F and B in terms of the categories.

in **Table 1.** The location of the initial wave front was taken to be near the wave front of the 1946 tsunami as estimated by Hatori (1974)[7].

3. Numerical Evaluation of Source Parameter Effects

3.1 Effect of duration time, T

First of all, the effect of the duration time was considered numerically. In this

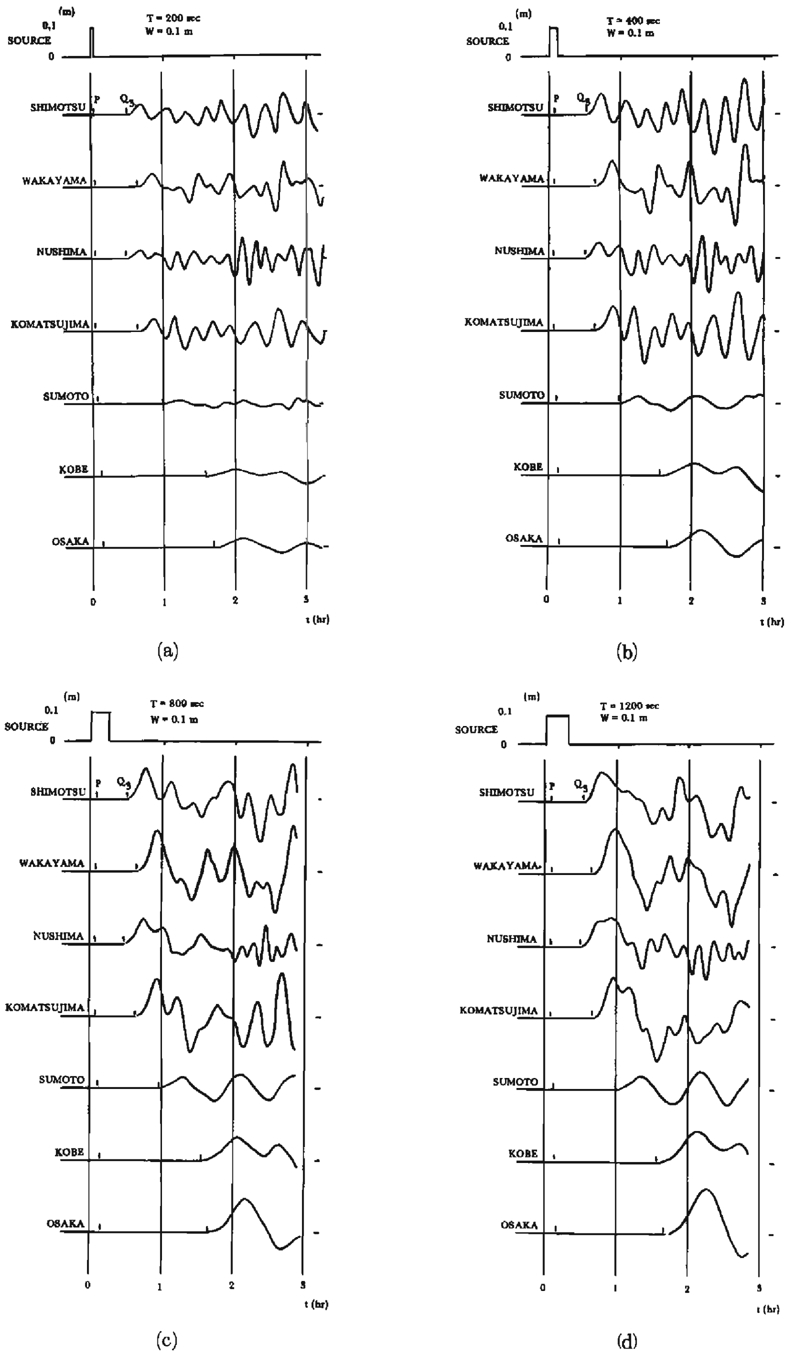

Fig. 2. Effect of duration time T to numerical tsunamis on the coast (scale of elevation at each station is the same as the scale for the source)
(a) T=200 sec, (b) T=400 sec, (c) T=800 sec and (d) T=1200 sec

case, the size of an equivalent source area was selected to be $D=3\Delta x$, $B=10\Delta y$, where $\Delta x=\Delta y=4540$ m), and its initial wave front propagating northwards was taken as that on the northern boundary of the equivalent source area for F(I) in **Table 1**, and the time step was taken to be $\Delta t=14.2$ sec with consideration of Neuman's condition for stability of numerical computation.

For convenience of numerical computation, the value of the disturbance displacement was taken to be $W=0.1$ m. This is the same as introducing two step functions (Heaviside's step functions) of $W_0=0.1$ m and $W_T=0.1$ m, and to consider $W(t)=W_0-W_T$, where T is defined as the duration time of the forcing function W(t). Strictly speaking, there is an ambiguity of the equivalent tsunami source function left because the forcing function or input function as a combination of the two step functions appears in every time step of Δt discretely. So that the input of W_0 contributes to all values of t of $n\Delta t$ (n: positive integer) except $t=0$. If $n\Delta t<T\leqslant(n+1)\Delta t$, then, W_T affects to the sea surface profile when $T\geqslant(n+1)\Delta t$. The duration time, T, affects the tsunami development along the coast as shown in **Fig. 2a** to **d**. The numerical evolution at the mesh points nearest to the tide stations corresponding to Osaka, Kobe, Sumoto, Komatsujima, Nushima, Wakayama and Shimotsu are shown in **Fig. 2**. The cases of **a**, **b**, **c** and **d** in **Fig. 2** are for T=200, 400, 800 and 1200 sec, respectively. As found in the figures, the pattern of the tsunami at a certain station varies with the value of T. The wave height increases with increase of the value of T. Tsunami evaluations for only three hours after occurrence of the disturbance with $W=0.1$ m are shown in **Fig. 2**.

Recently Nakamura (1980)[2] has defined two kinds of tsunami arrival times, P and Q. The time P is that when a disturbance appeared fifrst in the numerical computation. The time Q is that of ordinal arrival time of a tsunami as defined and used widely in practice. In this study, the time Q is taken as the time when the disturbance at the mesh point exceeds 1 mm and is denoted as Q_3. Referring to the numerical tsunami in **Fig. 2**, the times P and Q_3 at Shimotsu are P=3 min and $Q_3=30$ min, respectively. At Osaka, P=8.3 min and $Q_3=100$ min, respectively. Generally, the time difference between P and Q (or Q_3) depends on the distance of the mesh point to the naerest front at the source area. However, the times P and Q seem to be independent of the duration time, T numerically as far as the computed result in this study is concerned.

In order to clarify the properties of the leading wave, for example, at Osaka, the duration time, T, was related to the wave form of the leading wave in **Fig. 3**. Viewing **Fig. 3**, it is easily seen that the crest height of the leading wave becomes higher with increase of the duration time T within the range of 200 sec to 2000 sec. In addition, the crest of the leading wave appears later with increase of T.

3.2 Effect of the initial disturbance, W

The initial disturbance, W is an effective equivalent factor to the wave profile at each mesh point even when the other source parameters are fixed values. When

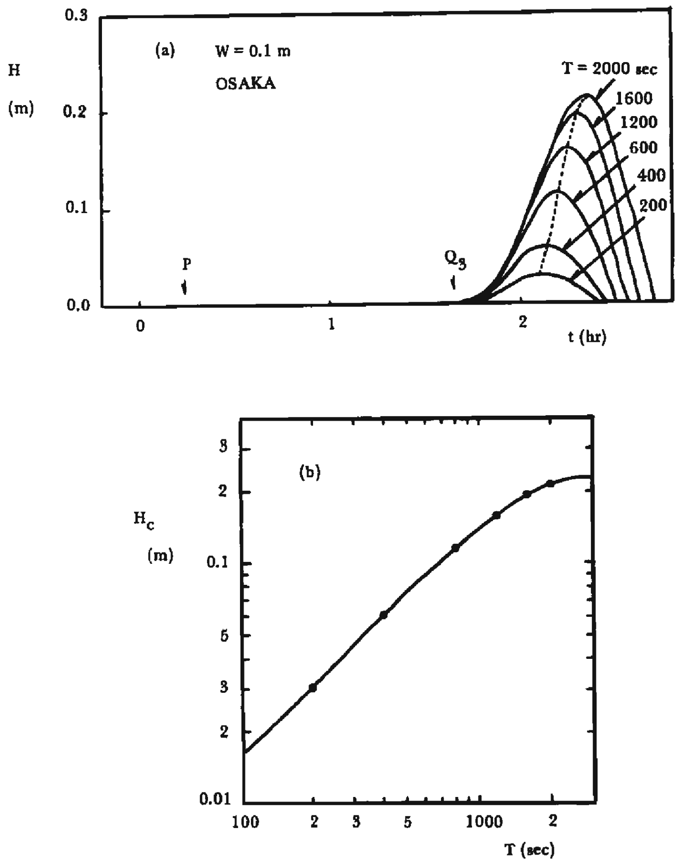

Fig. 3. Effect of duration time T to the leading wave at Osaka
(a) wave patterns of the leading wave for W=0.1 m
(b) relation between crest height H_c of the leading wave and initial disturbance W

we consider a case of T=400 sec and W in the range of 0.1 to 3 m for a fixed value of D, F, and B, i.e., D=2Δx, F for I=4 and B=10Δy, we can find a specific property of the leading wave of the tsunami. For example, at Wakayama as is shown in **Fig. 4a** to **c**. That is, the time P at Wakayama was 4.27 min for any value of W considered in this study. Water level, H, and the crest height H_c of the leading wave are functions of W. Judging from **Fig. 4a**, the crest of the leading wave appears at t=53.1 min for a value of W in the range of 0.1 to 3 m. We can easily find numerically that the crest height, H_c, is proportional to the initial disturbance, W as shown in **Fig. 4b**. The times, Q_3 and Q_2 for the disturbance exceeding 1 mm (10^{-3} m) and 1 cm (10^{-2} m) are related to the value of W on the diagramme in **Fig. 4c**.

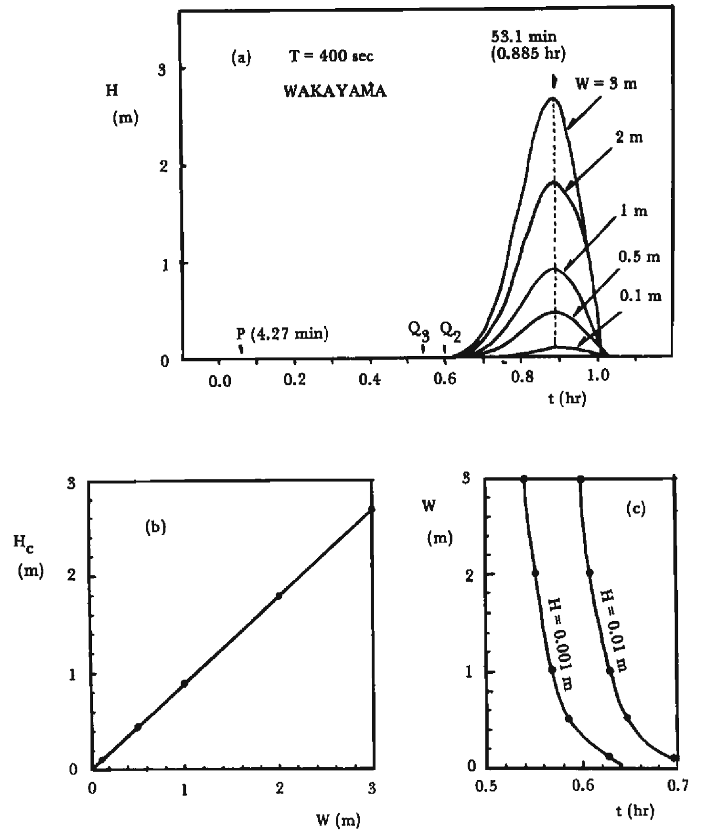

Fig. 4. Effect of initial disturbance W to the leading wave at Wakayama
(a) wave patterns of the leading wave for T=400 sec
(b) relation between crest height H_c of the laeding wave and initial disturbance W
(c) arrival time Q_3 and Q_2 as a function of W (see text for detail)

4. Numerical Tsunami Evolution and Source Area

In order to investigate the relation between the source area and the computed tsunami evolution, parameters in this section were taken to be W=0.1 m and T=400 sec.

4.1 Effect of the length, D

The effect of the length, D of the source area to the leading wave can be found in **Fig. 5**, for example, as found at Komatsujima for a fixed width, B of the source area as in **Fig. 1**. If we take $D=2\Delta x$, $3\Delta x$, $4\Delta x$ and $5\Delta x$ (where $\Delta x=4540$ m), and the location of the front F is fixed along I=10 to form the northern margin of the source area in the numerical model, then the crest height, H_c of the leading wave varies with the value of D. However, the time of the crest is numerically independent of D. The result shown in **Fig. 5b** seems to suggest that the crest height, H_c,

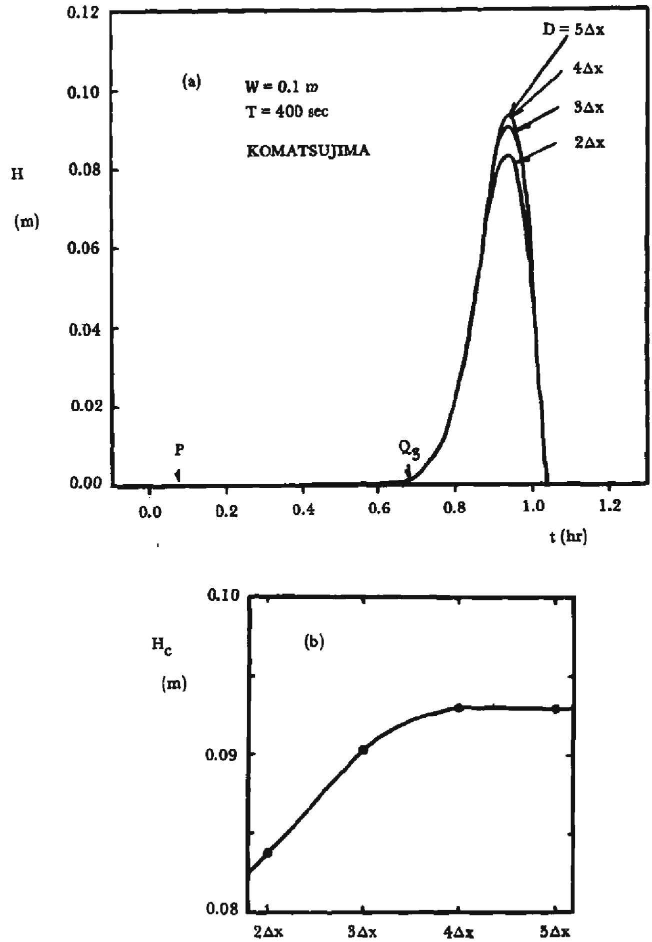

Fig. 5. Effect of length D of tsunami source to the leading wave at Komatsujima
(a) wave patterns of the leading wave for T=400 sec and W=0.1 m
(b) relation between crest height H of the leading wave and length D

is independent of the value of D if the value of D is greater than 15 km in the numerical model. The value of H_c decreases monotonously with decrease of the value of D. This means that the value of H_c can be small or negligible if the value of D is small enough because any disturbance in a small area is only a little source of energy at the time of wave generation. While, the value of H_c is the same at any mesh point if the value of D is large enough; for example, if it is larger than $4\Delta x$ in this numerical model. Then, if any actual tsunami-source area is large enough for the other fixed tsunami source parameters, waves along the coast must be same. This further suggests that there could exist any maximum of the crest height.

4.2 Effect of the width, B

Numerical computations were carried out for the two cases of D=3Δx with B=4Δy and B=10Δy (where Δx=Δy). The results for B=4Δy and for B=10Δy are shown respectively by full lines and dotted lines in **Fig. 6**. In this case, the two times, P and Q_3 are independent of the value of B. This numerical result seems to suggest that the dimension of B relative to the width of Kii Channel can be effective to induce a resonant oscillation in Kii Channel. In the numerical model, the wave height and the crest height are high if B is large. As for the numerical result shown in **Fig. 6**, it seems that the wave height and the crest height depend on B while a little shift of the time appears at the crests and troughs.

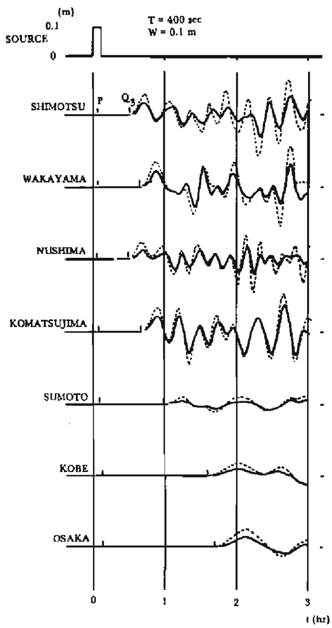

Fig. 6. Effect of width W of tsunami source to numerical tsunami on the coast (scale of elevation at each station is the same as the scale for the source)
(a) full line: B=4Δy
(b) dotted line: B=10Δy

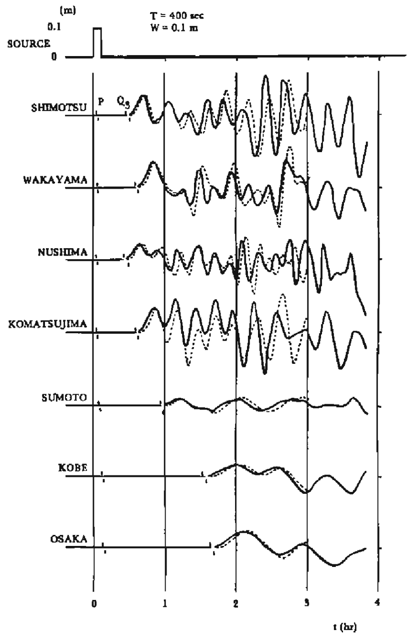

Fig. 7. Difference of phase of numerical tsunami on the coast caused by location of front (scale of elevation at each station is the same as the scale for the source)
(a) full line and time marks for P and Q_3 above the line: F for I=12
(b) dotted line and time marks for P and Q_3 below the line: F for I=10

4.3 Location of the front, F

A shift of the initial front at the source affects the arrival time and the phase of the numerical tsunami evolution as shown in **Fig. 7**. The dotted lines in **Fig. 7** are the same results as those in **Fig. 2b**, and the full lines show the numerical results after a shift of the initial front northward as much as $2\Delta x$. The times, P and Q_3, also shift corresponding to the phase shift of the tsunami evolution.

5. Discussion

The above numerical computations were carried out for a set of simplified parameters which were assumed to characterize the tsunami source as an equivalent surface condition. In reality, a more complicated condition for seismic parameters should be introduced to reproduce an actual tsunami in the source area. However, the author feels that an extensive study on tsunami energetics must be made in order to evaluate the total picture of the tsunami, which is yet to be accomplished.

The author could find no mareograms except at Shimotsu and at Osaka for the 1946 Tsunami and obtained a numerical result for only about three hours, so that it seems hard to compare the mareograms of the 1946 Tsunami with the numerical result to determine whether the numerical model has been simulated successfully. We could obtain five reliable mareograms for the 1944 Tsunami at Shimotsu, Wakayama, Sumoto, Kobe and Osaka respectively (JOTI, 1957)[11]. The author has never considered that the 1944 Tsunami is the same, but that it is similar to the 1946 Tsunami. Therefore he tried boldly to compare the mareograms of the 1944 Tsunami with the computed result in order to have a qualitative glance at the dynamics determined by the numerical model, as well as trying to find whether the numerical result is reasonable or possible, because we have no mareogram of the 1946 Tsunami along the coast of Kii Channel and Osaka Bay except at Shimotsu and Osaka. The author feels that it is too unreliable to confirm whether the numerical mdoel reproduced a tsunami referring to only two mareograms at Shimotsu and Osaka in the considered area.

Concerning the mareograms of the 1944 Tsunami, the author could not learn anything except the highest water level as stated by Aida (1979)[12]. Aida referred to this water level in his study, though the author decided to refer to mareograms rather than trace of the highest water level caused by tsunami inundation or run-up. The mareogram of the 1944 Tsunami at Kobe includes a variation which was caused by the relative motion of the tide gauge with the occurrence of the earthquake. Referring to this variation and the time of occurrence the earthquake, a time correction of the mareogram is given to confirm the exact configulation of the tsunami at Kobe, as shown in **Fig. 8**. Comparing **Fig. 8** with **Fig. 2**, it seems that the wave patterns in **Fig. 8** are more similar to those in **Fig. 2b** than the those in **Fig. 2**, although the locations of the wave source are different from each other. This suggests that the response function at each station is effective to determine the wave pattern even when the location of the wave source determines the input function, and this supports our experience with tsunamis except for the arrival time.

In the numerical modelling, the duration time, T, at the source area was taken to be in the range of 200 to 2000 sec. With the above reference, a reasonable value

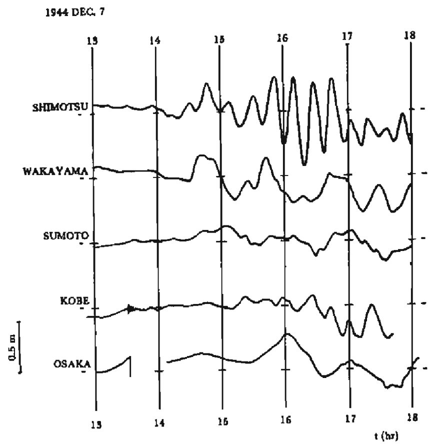

Fig. 8. Mareograms of the tsunami on 7 December 1944 (scale of elevation at each station is the same and time is in JST)

of T should be around 400 sec as found in **Fig. 2b**. This does not mean that the value of T can be directly related to the seismic parameters. In this case, the author never referred to any seismic factors, while Kanamori (1973)[10] remarked that the earthquakes were characterized by a phenomena of 10 to 20 sec in time scale and the resulting tsunamis could be generated with variations of time of several hundreds of seconds. On the other hand, according to Kajiura (1979)[13], the time scale of ground motion which generates a tsunami is 20 sec at most and velocity of the ground motion is less than 1 m/s. It seems that Kanamori's time of several hundreds sec is by chance in the same order as the value T=400 sec. The value of T=400 sec in the model was taken speculatively so that there is no reasoning yet for selecting the value of T with dynamical consideration but with a personal prejudice. Hence, the author tends to consider that there must be some possibility to relate the value of T in the numerical model to Kanamori's time scale which was derived on the basis of seismic data. In addition, the author considers it necessary to notify what he feels uneasy. The author, being not so familiar with seismology or earthquakes, feels it reasonable to consider that the scale of a fault or area of significant displacement caused by any earthquake is larger under the sea than on the land. In fact, existing seismology tells us that the scale or area under the sea versus that on the land are significantly different from each other while the area on the land affected by an earthquake is located not so far from the area under the sea where the big tsunamigenic earthquake occurs. This distance is several tens of kilometers at most. Of course, tectonophysics have been developed which give physical reasons for plate tectonics as well as source mechanisms of earthquakes. In spite of this, the author feels there must be yet additional problems. This is partly the reason why the author tends to consider a small area of a tsunami source in the numerical model to be possible and reasonable. The author understands that the size of the fault on the land can be confirmed directly by survey or observation while it must be still hard to give exact information of the scale of a fault under the sea. In addition to the above, the numerical result of time when the initial disturbance appears first at time P at each mesh point in the model seems to support a possibility for assuming a small area of tsunami source as an equivalent input or forcing condition.

As for leading wave, Kajiura (1963)[14] has already developed a linear theory for a simplified boundary condition with a constant water depth. In the present numerical study, the linearized model gave a 1% difference of the height at the crest of the leading wave from a nonlinear model which included the effects of advection, bottom friction, and the earth's rotation and a more realistic bathymetric condition. This result suggests that the present numerical model can be utilized practically to find the profile of a tsunami without any consideration of the terms for advection, bottom friction, and the earth's rotation. For the details of the tsunami in the coastal zone, we have to consider transformation of waves caused by shoaling, refraction, diffraction and nonlinear effect of the water surface curvature at the crest of the wave. Of course, we have to recall that the curvature of the sea surface was taken to be negligible in the numerical model. However, a linear model can be utilized for practical use to evaluate tsunami height in an area of interest.

Inverse tsunami propagation charts have been utilized to estimate source areas (for example, Nakano, 1978)[15]. In the past, the time corresponding to the time Q_3 has been taken as the arrival time of tsunamis. Regarding the time Q_3 for the preparation of the inverse tsunami propagation chart, the estimated source area, which is encircled by the initial location of the front, should be more than several times that of the actual source area. In order to find a more exact or reasonable area, we must find the time P and refer to the time P in making an inverse tsunami propagation chart, although it is difficult to identify the time corresponding to the time P on any mareogram at present. Of course, an exact evaluation of the propagation velocity is essential to find the exact source area.

An interesting example has been given for the two times, P and Q. It is found in Munk's writing (1980)[16]. Actually, it is better to cite a part of Munk's manuscript exactly as written:

'..... After witnessing the explosion (of 1951 nuclear test IVY-MIKE) at this chosen range, and seeing no wave signal for 11 minutes thereafter (the computed time was 6 minutes following the land slide), we transfered to the HORIZON (the Scripps vessel) and steamed north at full speed to avoid radioactive fallout (unsuccessfully as it turned out). We returned in two days to pick up the rafts and instrumentation. I unspooled the records, checking the time mark made prior to my leaving the raft. Within 90 seconds following the final time mark, my wave recorder had malfunctioned, giving a signature equivalent to a huge tidal wave. It is true the "event" occurred too late to be consistent with computations .....'.

As we read, in Munk's case, the time P for the explosion seems left to be unawared but the time Q_3 for that could be found as 'a signature equivalent to a huge tidal wave'. Similar to this, the author tends to take it possible that the disturbance appeared too late to be consistent with a prediction of tsunami occurrence at Osaka because the initial disturbance at the time P was too small to distinguish it to be the tsunami signature but that the time Q_3 could be read from the computed water level at Osaka as found in **Fig. 6** or **7**. This must be cause of that 'the "event" occurred too late to be consistnet with computations .....'.

Even with the above discussion, it is still too early to consider a realistic evaluation of tsunamis, simply referring to only one case study. However, the author tends to take it to be proper to assume the source area for the numerical computation to be about $10\,km \times 50\,km = 500\,km^2$. The order of the source area in the south of Japan previously estimated by the inverse propagation method (for example, Hatori, 1974)[7] was, for example, about $100 \times 200\,km^2 = 2 \times 10^4\,km^2$ for the 1944 Tsunami. This source area is about 40 times that assumed in the present numerical computation. What is the exact source area should be confirmed for each particular day in order to relate an equivalent tsunami source with a combination of tsunami parameters to the seismic parameters of a tsunamigenic earthquake. Then, the author believes, at this time, that it is possible and reasonable to take such a small area for the tsunami source instead of that estimated previously even without any dynamic consideration.

6. Conclusion

Tsunamis intruding into a bay were studied within the scope of a numerical experiment by using a simple finite difference method. For this purpose a tsunami model of Osaka Bay and Kii Channel was considered. The tsunami source condition was characterized by a combination of parameters for the sea surface in the source area, i.e., displacement, duration time and its location. As a result, a numerical tsunami evolution with the duration time of about 400 sec was considered as the most reasonable compared to the others in the model. It was found that the leading wave in the model was characterized numerically by a combination of the tsunami source parameters. Tsunami arrival time was discussed on the basis of the numerical results.

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